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14. ABSTRACT
This project had two main components: the a) initiation and b) propagation aspects of coronal mass ejections (CMEs) from the Sun that are directed towards the Earth.

In the context of stellar coronal field dynamics leading to CME initiation, the major outcomes from this project are that i) only the total amount of magnetic flux content in solar active regions and not their non-potentiality (or current content) governs coronal X-ray emission, ii) Kink-instability does seem to play an important role in the initiation of solar storms.

With regard to the propagation aspects, the work done in this project has resulted in three specific outcomes – i) an explicit demonstration of the fact that the Lorentz self-force acting on CMEs arises from misaligned currents and magnetic fields, ii) a recognition that solar wind drag on slow CMEs might only be effective for heliocentric distances greater than 60 to 80 solar radii, and iii) a clear elucidation of the role cross-field diffusion plays in mediating the interaction between galactic cosmic rays and magnetic field compressions caused by CMEs and their associated shocks near the Earth.

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Final Report for AOARD Grant FA2386-13-1-4057

Initiation and propagation of Earth-directed Coronal Mass Ejections (CMEs)

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Abstract:

This project had two main components: the a) initiation and b) propagation aspects of coronal mass ejections (CMEs) from the Sun that are directed towards the Earth.

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Introduction:

Solar eruptive events such as flares and Coronal mass ejections (CMEs) from the Sun are now widely recognized as the primary drivers of disturbances in the near-Earth space environment. With our increasing reliance on space-based technologies that can be quite vulnerable to such disturbances, it is imperative to acquire a thorough understanding of the factors governing the initiation of solar storms and their subsequent propagation from the Sun to the Earth (as CME flux ropes or magnetic clouds). This understanding is expected to contribute towards constraining reliable models for forecasting the occurrence and strength of space weather disturbances.

Experiment: The work done in this project has relied on theoretical and computational tools and analysis of space-based data that is available at no cost over the internet.

Results and Discussion:

Solar storms such as flares and CMEs are initiated in the overlying coronal flux systems associated with solar active regions. While it is believed that the magnetic properties of sunspots and active region flux systems and their dynamics (perhaps also driven by near-surface flows or coronal reconnection) govern whether these flux systems can generate a solar storm, a thorough understanding is missing. One aspect of this project was to look at the role of magnetic properties of solar active regions in the initiation of coronal activity and solar storms.

In this context, we have the following results to report. Comparing the magnetic properties of multiple solar active regions to their coronal X-ray emissivity (utilizing high-resolution data from the Hinode satellite), we have found that it is primarily the total magnetic flux content of active regions that govern the amount of coronal X-ray emission they generate (Hazra and Nandy 2015). Surprisingly, we have found that the total current or non-potentiality of active regions does not play a role in coronal X-ray emission, pointing out that the mechanism of coronal heating may be somewhat decoupled from the processes that lead to solar storms.

A big controversy in the field is whether the kink instability mechanism in strongly twisted active region flux systems can generate solar storms. Utilizing a new theoretical technique for measuring the magnetic twist (non-potentiality) of active regions, we find that active regions which host kink-unstable flux tubes have a statistically significant tendency to flare (Panja, Hazra, Nandy and Ravindra 2015). This indicates that kink instability is a viable mechanism for the initiation of solar storms.

In an alternative study, in an unanticipated collaboration during this project, we have written a comprehensive review of magnetic field generation and dynamics in the Sun and Solar-like active stars which modulate their space environment via their variable magnetic output (Brun et al. 2015).

The work done on CME propagation in this project has impacted two key issues in the field: Lorentz self-force driving and aerodynamic drag. A comprehensive physical understanding of these forces is essential in building a reliable model of CME propagation, which in turn can lead to accurate arrival time predictions. In explicitly showing that magnetic fields and currents in driven flux rope structures are substantially misaligned, our work (Subramanian et al 2014) has moved beyond the current state of the art, where Lorentz self-forces are computed using an equivalent inductance. This has also paved the way for future work that can investigate flux rope CMEs can remain as non-force-free structures. There is some evidence pointing to the fact that even magnetic clouds detected near the Earth are not force-free, and it needs further investigation. On the other hand, our work on quantifying the role of aerodynamic drag, especially for slower CMEs (Sachdeva et al 2015), has shown that CMEs might be subject to Lorentz self-forces might for much longer than is currently thought. The methodology used in this work, which involves using detailed measurements of CME cross-sections (which are frequently not circular), can spur further research on Lorentz self-forces and help better constrain the current distributions inside such flux rope CMEs.

Galactic cosmic rays have proved to be interesting probes for investigating the near-Earth structure of CMEs. Our work in this project has shown that cross-field diffusion of high energy cosmic rays through the turbulent sheath region between the CME and its shock is the principal cause of cosmic ray Forbush decreases. In doing so, we have quantified, for the first time, the turbulence levels in the sheath region. Further work can involve precursors to Forbush decreases which can help us constrain turbulence levels in the quiescent region between the Earth's magnetosphere and the shock. Taken together, these results can help provide considerable advance information about the ram pressure and shock strength of the magnetic field enhancement that impacts the Earth's magnetosphere.

List of Publications and Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

Papers published in peer-reviewed journals:

Self-similar Expansion of Solar Coronal Mass Ejections: Implications for Lorentz Self-force Driving, P. Subramanian, K. P. Arunbabu, A. Vourlidas and A. Mauriya, 2014, Astrophysical Journal, vol. 790, p. 125

The Relationship between Solar Coronal X-Ray Brightness and Active Region Magnetic Fields: A Study Using High Resolution Hinode Observations, S. Hazra and D. Nandy, Solar Physics, 2015, vol. 290, p. 771

The Solar-Stellar Connection, A.S.Brun, R.A. Garcia, G. Houdek, D. Nandy and M. Pinsonneault, Space Science Reviews, in press (doi: 10.1007/s11214-014-0117-8)

Manuscripts submitted to peer-reviewed journals:

How are Forbush decreases related with interplanetary magnetic field enhancements?, K. P. Arunbabu, H. M. Antia, S. R. Dugad, S. K. Gupta, Y. Hayashi, S. Kawakami, P. K. Mohanty, A. Oshima, P. Subramanian, 2015, submitted to Astronomy and Astrophysics

CME propagation: where does aerodynamic drag ``take over''?, N. Sachdeva, P. Subramanian, R. Colaninno, A. Vourlidas, 2015, submitted to the Astrophysical Journal

Copies of all these papers can be downloaded from:
https://www.dropbox.com/sh/nlwknwvlz952bp0/AACbirvwo2CosVV9gfkOFh4Ha?dl=0

Manuscripts in preparation:

Solar Active Regions with Kink-Unstable Flux Systems are more likely to Generate Flares, M. Panja, S. Hazra, D. Nandy, B. Ravindra, 2015, in preparation

Significant collaborations with US scientists:

The work done in this project has enabled collaboration with Dr Angelos Vourlidas (now at the Applied Physics Lab, Johns Hopkins University, formerly at the Naval Research Lab), Dr Robin Colaninno (Naval Research Lab) and provides a platform for continued work in the future. The project also enabled collaboration, data sharing and discussions with Dr. Edward DeLuca of Harvard Smithsonian Center of Astrophysics in the context of the Hinode satellite data which is a JAXA mission in collaboration with NASA.